

## Final Report for NAG5-100

This document is a final technical report for grant NAG5-100, entitled "Research in X-ray Astronomy", which expired on June 30, 1997.

This research grant supported an active sounding rocket program at Penn State University over a period of over 10 years. During this period, the grant supported at least 8 graduate students in Astronomy & Astrophysics for at least a portion of their research. During the same period, our group was involved in seven sounding rocket flights, launched from White Sands, New Mexico, and from Woomera, Australia.

Most of these rocket flights, and most of the work supported by this grant, involved the use of X-ray CCD cameras. The first X-ray CCD camera ever flown in space was our sounding rocket observation of SN1987A (flight 36.030 in 1987). Subsequent flights utilized improved CCD detectors, culminating in the state-of-the-art EEV detector developed for our CUBIC mission, which was flown on 36.093 last May. Data from the last three flights, which observed the diffuse X-ray background with CCDs, include detection of the OVII He $\alpha$  line in the high latitude diffuse background (36.092, Fig. 1) and detection of the Mg XI He $\alpha$  line in the North Polar Spur (36.092, Fig. 2). These results have been reported at meetings of the American Astronomical Society (Mendenhall *et al.* 1996, *Bull. AAS*, 28, 1283) and the SPIE (Mendenhall *et al.* 1996, *Proc. SPIE*, 2808, 34). The analysis of flights 36.092 and 36.106 is part of Jeff Mendenhall's PhD thesis (PSU, 1998) and will be published in the Astrophysical Journal next year. The 36.093 data are currently being analyzed by PhD student Laura Cawley.

From 1990 to 1996 this grant supported our development and launch of the CUBIC instrument on the SAC-B satellite, which was designed to measure the spectrum of the soft X-ray diffuse background with moderate energy resolution and high S/N ratio. Unfortunately, this mission terminated shortly after launch due to a failure of the Pegasus XL launch vehicle. This work resulted in publication of 4 papers in the SPIE Proceedings and four others in refereed journals, in addition to several other conference proceedings and contributed papers.

In addition to the CCD flights described above, this grant has supported preliminary development of a new sounding rocket payload utilizing a replicated Ni mirror that is being developed at PSU in collaboration with MSFC. Initial testing of the coating technology has produced promising results.

The work carried out under grant NAG5-100 is now being continued under a new grant number, NAG5-5093.



# Typical Diffuse Background Region (36.092 MHz)

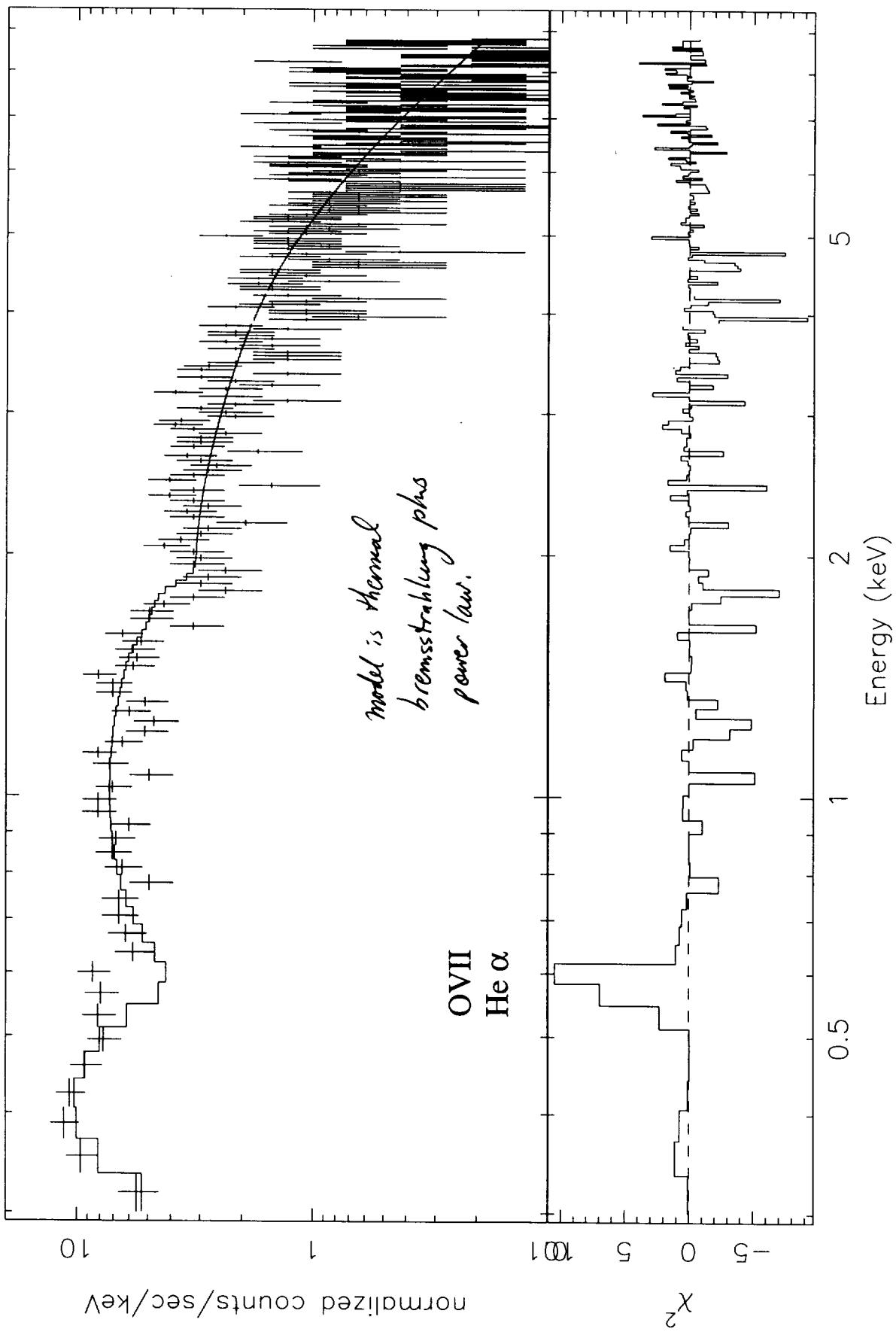


Fig. 1

jam 23-Mar-1998 23:22

The North Polar Spur (36,093 ut)

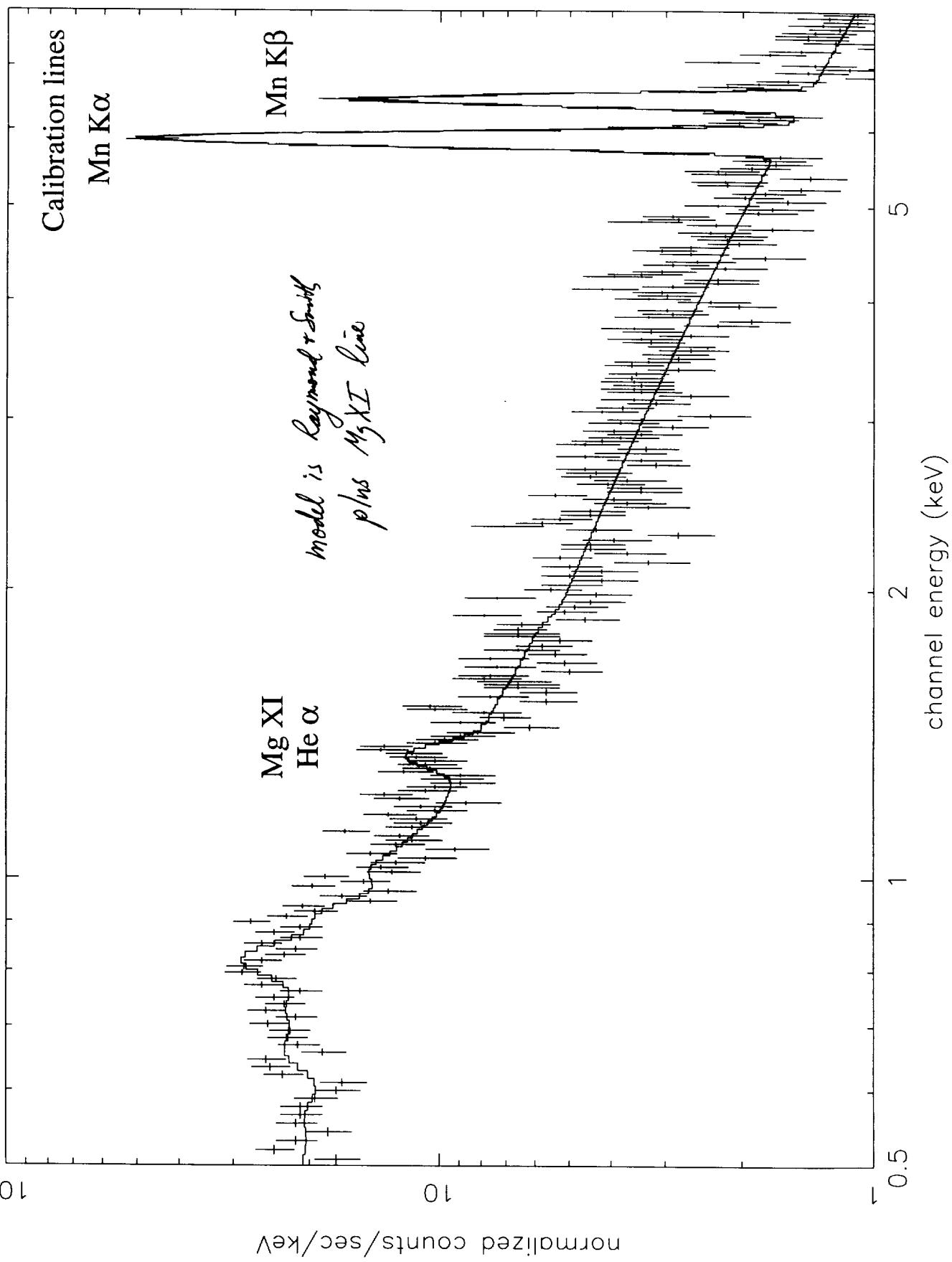


Fig. 7

## Bibliography

### Refereed Publications:

Kraft, R. P., Burrows, D. N., Garmire, G. P., & Nousek, J. A. 1996, "Thin Gate Frontside Illuminated CCDs versus Backside Illuminated CCDs for X-ray Astronomy", *The Astrophysical Journal (Letters)*, 466, L51–L54

Kraft, R. P., Nousek, J. A., Lumb, D. H., Burrows, D. N., Skinner, M. A., & Garmire, G. P. 1995, "Measuring the Soft X-ray Quantum Efficiency of Charge-Coupled Devices Using Continuum Synchrotron Radiation", *Nuclear Instruments & Methods A*, 366, 192–202

Kraft, R. P., Burrows, D. N., Garmire, G. P., Nousek, J. A., Janesick, J. R., and Vu, P. N. 1995, "Soft X-ray Spectroscopy with Sub-Electron Readnoise Charge-Coupled Devices", *Nuclear Instruments & Methods in Physics Research A*, 361, 372–383

Berthiaume, G. D., Burrows, D. N., Garmire, G. P., & Nousek, J. A. 1994, "CCD Soft X-ray Observations of the Puppis A SNR", *The Astrophysical Journal*, 425, 132–141

Antunes, A., Burrows, D. N., Garmire, G. P., Lumb, D., & Nousek, J. A. 1993, "A Predictive Model for Space-Based CCD Degradation", *Experimental Astronomy*, 4, 159–175

Burrows, D. N., & Kraft, R. P. 1993, "On the Source Function of the Soft X-ray Diffuse Background", *The Astrophysical Journal*, 411, 685–689

Burrows, D. N., Singh, K. P., Nousek, J. A., Garmire, G. P., & Good, J. 1993, "A Multiwavelength Study of the Eridanus Soft X-ray Enhancement", *The Astrophysical Journal*, 406, 97–111

Kraft, R., Burrows, D.N., & Nousek, J.A. 1991, "Determination of Confidence Limits for Experiments with Low Numbers of Counts", *The Astrophysical Journal*, 374, 344–355

Burrows, D.N., Nousek, J.A., Berthiaume, G.D., & Garmire, G.P. 1989, "Search for Soft X-ray Emission from SN1987A with a CCD X-ray Imaging Spectrometer", *The Astrophysical Journal*, 347, 1114–1118

Burrows, D.N. 1989, "Observational Constraints on an Embedded Cloud Model for the Soft X-ray Diffuse Background", *The Astrophysical Journal*, 340, 775–785

Nousek, J.A., Garmire, G.P., Pipetti, R.J., Burrows, D.N., Ku, W.H.-M., & Lum, K.S.K. 1988, "Diamond-turned lacquer-coated soft X-ray telescope mirrors", *Applied Optics*, 27, 1430–1432

### Conference Proceedings:

Burrows, D. N., Grant, C. E., Cawley, L. J., Garmire, G. P., Mendenhall, J. A., Nousek, J. A., & Skinner, M. A. 1996, "CUBIC: Preflight Calibration Results and Initial

Operations”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy VII*, ed. O. H. W. Siegmund & M. A. Gummin, *Proc. SPIE*, 2808, 48–58

Mendenhall, J. A., Burrows, D. N., Cawley, L. J., Cocklin, E. J., Garmire, G. P., Kraft, R. P., & Nishikida, K. 1996, “X-ray CCD Sounding Rocket Observations of the Soft X-ray Background from 0.2 to 10 keV”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy VII*, ed. O. H. W. Siegmund & M. A. Gummin, *Proc. SPIE*, 2808, 34–47

Burrows, D. N., Skinner, M. A., Catalano, M. A., Cawley, L. J., Cocklin, E. J., Engel, L. G., Entingh, T. J., Garmire, G. P., Green, R., Janches, D., Kelly, D. A., Mendenhall, J. A., Nosek, J. A., Lumb, D. H., Holland, A. D., and Pool, P. 1995, “CUBIC: X-ray CCD Spectroscopy of the Diffuse X-ray Background”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy VI*, ed. O. H. W. Siegmund & J. V. Vallerga, *Proc. SPIE*, 2518, 141–162

Skinner, M. A., Burrows, D. N., Garmire, G. P., Mendenhall, J. A., Lumb, D. H., Holland, A. D., and Pool, P. 1995, “CUBIC: Preflight Calibration Status”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy VI*, ed. O. H. W. Siegmund & J. V. Vallerga, *Proc. SPIE*, 2518, 163–178

Cawley, L. J., Nosek, J. A., Burrows, D. N., Garmire, G. P., and Janches, D. 1995, “CCD X-ray Detectors: On-Board Data Processing”, in *Proc. SPIE*, 2518, 179–187

Kraft, R. P., Burrows, D. N., Garmire, G. P., Lumb, D. H., Nosek, J. A., Skinner, M. A., Janesick, J. R., Elliot, T., Collins, S. A., & Vu, P. 1994, “Soft X-ray Spectroscopy using Charge-Coupled Devices with Thin Poly Gates and Floating Gate Output Amplifiers”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy V*, *Proc. SPIE*, 2280, 320–332

Skinner, M. A., Burrows, D. N., Garmire, G. P., Kraft, R. P., Lumb, D. H., and Nosek, J. A. 1993, “CUBIC: Laboratory Testing of Thin Poly CCDs”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy IV*, ed. O. H. W. Siegmund, *Proc. SPIE*, 2006, 258–264

Skinner, M. A., & Burrows, D. N. 1993, “CUBIC: filters and the space environment”, in *EUV, X-ray and Gamma-ray Instrumentation for Astronomy IV*, ed. O. H. W. Siegmund, *Proc. SPIE*, 2006, 31–38

Skinner, M. A., Burrows, D. N., Garmire, G. P., Lumb, D. H., & Nosek, J. A. 1993, “The CUBIC Cosmic X-ray Background Experiment”, in *Massive Stars: Their lives in the Interstellar Medium*, ed. J. P. Cassinelli and E. B. Churchwell, ASP Conference Series, 35, 531–533

Burrows, D. N., Skinner, M. A., Antunes, A. J. D., Catalano, M. A., Cocklin, E. J., Engel, L. G., Entingh, T. J., Garmire, G. P., Green, R., Kelly, D. A., Kraft, R. P., Lumb, D. H., Malakoff, S. L., Mendenhall, J. A., & Nosek, J. A. 1992, “CUBIC: a non-dispersive diffuse X-ray background spectrometer”, in *EUV, X-ray*,

*and Gamma-ray Instrumentation for Astronomy III*, ed. O. H. W. Siegmund (*Proc. SPIE*, 1743), 72–82

Nousek, J.A., Berthiaume, G.D., Burrows, D.N. & Garmire, G.P. 1992, “CCD X-ray Observations of Puppis A”, in *From Ginga to Astro-D and Further to DUET*, ed. F. Nagase (*ISAS Symposium on Space Astrophysics (Feb. 4–5, 1992)*), (Tokyo), 99–103

Burrows, D. N., Garmire, G. P., Lumb, D. H., & Nousek, J. A. 1991, “The CUBIC Experiment”, in *The X-ray Background*, ed. X. Barcons and A. Fabian (proceedings of international workshop in Laredo, Spain, Sept 11–13, 1991), 277–281

Burrows, D. N. 1990, “Observational Constraints on an Embedded Cloud Model for the Soft X-ray Diffuse Background”, in *Evolution of the Interstellar Medium*, ed. L. Blitz, (*A.S.P. Conference Series Vol. 12*), 303–304

Burrows, D. N., Berthiaume, G. D., Catalano, M. A., Entingh, T. J., Garmire, G. P., Larkin, C., Nousek, J. A., & Weaver, G. M. 1989, “A Low-Cost, Versatile CCD controller”, in *CCDs in Astronomy*, ed. G. Jacoby, (*A.S.P. Conference Series Vol. 8*), 165–170

Burrows, D. N., Berthiaume, G. D., Catalano, M. A., Garmire, G. P., Larkin, C., Marks, F., Nousek, J. A., & Weaver, G. M. 1989, “Penn State Imaging X-ray Spectrometer”, in *EUV, X-ray, and Gamma-ray Instrumentation for Astronomy and Atomic Physics*, ed. C. J. Hailey and O. H. W. Siegmund (*Proc. SPIE*, 1159), 92–104

Nousek, J.A., Garmire, G.P., Pipetti, R.J., Burrows, D.N., Ku, W.H-M., & Lum, K.S.K. 1987, “Diamond Turned, Lacquer Coated Soft X-ray Telescope Mirrors”, in *Grazing Incidence Optics for Astronomical and Laboratory Applications*, ed. S. Bowyer and J. C. Green (*Proc. SPIE*, 830), 95–97

Burrows, D. N. 1984, “Local Contributions to the 1 keV Diffuse Background”, in *IAU Colloquium #81, Local Interstellar Medium*, ed. Y. Kondo, F.C. Bruhweiler and B.D. Savage (*NASA Conference Publication 2345*), 215–218

## Contributed Papers:

D. N. Burrows, J. A. Nousek, & G. P. Garmire 1997, “CUBIC2: Spectroscopy of the Diffuse X-ray Background”, *Bull. AAS*, 29(5), 1300

K. Nishikida & D. N. Burrows 1997, “Multiwavelength Observations of the Loop I Superbubble”, *Bull. AAS*, 29(5), 1297

Burrows, D. N., Mendenhall, J. A., & Garmire, G. P. 1997, “CCD Sounding Rocket Observations of the Diffuse X-ray Background”, paper presented at the 1997 meeting of the High Energy Astrophysics Division of the American Astronomical Society, 4–7 November, 1997

Burrows, D. N., & Moskalenko, E. I. 1997, "CUBIC-II: Spectroscopy of the Diffuse X-ray Background", paper presented at the 1997 meeting of the High Energy Astrophysics Division of the American Astronomical Society, 4–7 November, 1997

Burrows, D. N., & Guo, Z. 1997, "Measurements of the Size and Pressure of the Local Bubble towards Eridanus", IAU Colloquium No. 166, "The Local Bubble and Beyond", held in Garching bei München, Germany, 21–24 April, 1997

Burrows, D. N., Garmire, G. P., Moskalenko, E. I., Nousek, J. A., & Skinner, M. A. 1996, "CUBIC: The Cosmic Unresolved Background Instrument using CCDs", *Bull. AAS*, 28(4), 1283

Mendenhall, J. A., Burrows, D. N., Cawley, L., Cocklin, E. J., Garmire, G. P., Kraft, R. P., & Nishikida, K. 1996, "CCD Sounding Rocket Observations of the Soft X-ray Background", *Bull. AAS*, 28(4), 1283

Burrows, D. N., Skinner, M. A., Nousek, J. A., & Garmire, G. P. 1996, "CUBIC: Measuring the X-ray background from 0.2 - 10 keV", AAS HEAD 1996 meeting, San Diego, California, May 3-4, 1996

Burrows, D. N., Skinner, M. A., Nousek, J. A., & Garmire, G. P. 1995, "CUBIC: An X-ray Spectrometer for the Diffuse X-ray Background", *Bull. AAS*, 27(2), 817

Skinner, M. A., Burrows, D. N., Garmire, G. P., Lumb, D. H., & Nousek, J. A. 1993, "The CUBIC Cosmic X-ray Background Experiment", *Bull. APS*, 38(2), 920

Burrows, D. N., Garmire, G. P., Lumb, D. H., & Nousek, J. A. 1991, "The CUBIC Experiment", *Bull. AAS*, 23(4), 1452

Berthiaume, G. D., Burrows, D. N., Garmire, G. P., & Nousek, J. A. 1990, "CCD Soft X-ray Imaging Spectroscopy of the Puppis A Supernova Remnant", *Bull. AAS*, 22(4), 1252

Berthiaume, G.D., Burrows, D.N., Nousek, J.A., & Garmire, G.P. 1989, "Modelling and Testing of CCDs for X-ray Astronomy", *Bull. AAS*, 21(4), 1076

Kraft, R. P., Burrows, D. N., & Nousek, J. A. 1990, "The Calculation of Upper and Lower Limits in Counting Experiments, with Low Numbers of Counts", *Bull. AAS*, 22(1), 738

Berthiaume, G.D., Burrows, D.N., Nousek, J.A., & Garmire, G.P. 1988, "Upper Limits on the Soft X-ray Flux from SN1987A", *Bull. AAS*, 20, 960

Burrows, D.N. 1988, "Observational Constraints on an Embedded Cloud Model of the Soft X-ray Diffuse Background", *Bull. AAS*, 20, 1061

Nousek, J.A., Burrows, D.N., & Garmire, G.P. 1987, "Sounding Rocket Soft X-ray Observations of SN1987A", *Bull. AAS*, 19, 1101

Burrows, D., Nousek, J., & Garmire, G. 1987, "Supernova 1987A in the Large Magellanic Cloud", IAU Circular No. 4494

Burrows, D.N. 1986, "Observational Constraints on Embedded Cloud Models of the Soft X-ray Diffuse Background", *Bull. AAS*, 18, 849

Burrows, D.N. 1984, "Local Contributions to the 1 keV Diffuse Background", *Bull. AAS*, 16, 466